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LAMINAR COMBUSTION AT HIGH TEMPERATURES AND PRESSURES

FINAL REPORT

JAMES C. KECK

JULY 30, 1981

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Burning velocities of practical fuel-air mixtures of interest for internal combustion engines were measured at high temperature and pressure using the constant volume bomb method. In addition the total hydrocarbons in the combustion products were measured using a flame ionization detector. The fuels investigated included methane, propane, isooctane, methanol and indolene. The measurements covered fuel-air equivalence ratios from 0.7 to 1.6, pressures from 0.4 to 50 atm., unburned gas temperature from 298 to 700 K and residual gas

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20. Abstract (continued)

mass fractions from 0 to 0.2. Over the range of conditions studied, the burning velocities can be fit within ±10% by a function of the form $S_u = S_{uo} (T_u/T_o)^{\alpha} (p/p_o)^{\beta}(1 - 2.1f)$ where S_{uo} is a reference for velocities which depend on fuel type and equivalence ratio, α and β are temperature and pressure exponents which are independent of fuel type and depend weakly on equivalence ratio and f is the residual gas mass fraction. The unburned hydrocarbons were found to come mainly from fine crevices in the bomb wall into which the flame could not propagate. The contribution from wall quench layers was very small and indicated greater than 95% oxidation of the initial quench layer due to diffusion into the hot combustion products.

1. INTRODUCTION

The research program described in this report was carried out during the period February 1, 1978 through December 31, 1980. The major funding was provided by ARO contract No. DAAG29-78-C-0010. Additional support was provided by NSF grant No. ENG77-14661.

The primary objective of the research was the measurement of laminar burning velocities for practical fuel-air mixtures at the high temperatures and pressures characteristic of internal combustion engines and burners. A secondary objective was the measurement of total hydrocarbon concentrations in the combustion products produced by burning in closed chambers. Such data are important for the development of combustion models for practical engines and burners which can be used to improve their fuel economy and reduce the air pollution they produce. They are also important for testing basic theoretical models of flame propagation and wall quenching.

Detailed accounts of the measurement techniques and experimental results are given in the 4 Reports and 2 Theses listed under Publications. A brief description of the experimental facility and the major results is given in the following 3 sections.

2. EXPERIMENTAL FACILITY

The measurements were carried out in a spherical combustion bomb having an inside diameter of 15.24 cm and equipped with two extended electrodes to provide central ignition. The bomb was designed for pressures up to 700 atm and was contained in an oven which could be heated up to 500 K. Initial gas pressures were measured by calibrated Bourdon gauges and mercury manometers. The dynamic pressure rise during combustion was measured by a Kistler piezoelectric transducer. Three ionization probes were used to detect the arrival of the flame front at the wall and check for spherical symmetry. An internal consistency check on the analysis was provided by a laser shadowgraph system which measured the arrival time of the flame front at a precisely known radius. A Beckman flame ionization detector was used to measure total hydrocarbons in the combustion products. A computer controlled analog to digital system was used for on line data acquisition and processing.

3. BURNING VELOCITY MEASUREMENTS

Burning velocities as a function of unburned gas temperature during combustion were determined from the measured dynamic pressure using a thermodynamic model which assumed frozen, unburned gas composition and equilibrium burned gas composition. Corrections for finite flame thickness, heat losses, buoyancy and charge stratification were estimated and found to be negligible.

The fuels studied were methanol, propane, isooctane and indolene. The oxidizer

was air. Residual combustion products in the unburned gas were simulated by a mixture of 85% N_2 and 15% CO_2.

The measurements covered the range of fuel-air equivalence ratios $\phi = 0.8$ to 1.4, diluent mass fractions $f = 0$ to 0.2, pressures $p = 0.4$ to 60 atm and unburned gas temperatures $T_u = 300$ to 700 K. For temperatures above 350 K, the data for all fuels could be fit within ±10% by the simple power law

$$S_u = S_{uo}\,(T_u^o/T_o)^{\alpha}(p/p_o)^{\beta}(1 - 2.1f)$$

where

$$S_{uo} = B_m + B_2\,(\rho - \rho_m)^2$$

$$\alpha = 2.18 - 0.8\,(\phi - 1)$$

$$\beta = -0.16 + 0.22\,(\phi - 1)$$

$$T_o = 298\ \text{K}$$

$$p_o = 1\ \text{atm}$$

and the constants B_m, B_2 amd ϕ are given in Table 1. Note that S_{uo} is a weakly decreasing function of increasing molecular weight while, within experimental error, α and β are independent of fuel type. In regions of overlapping data the results of this study agree well with those of previous studies.

4. HYDROCARBON CONCENTRATIONS IN COMBUSTION PRODUCTS

Total hydrocarbon concentrations in the products exhausted from the bomb following combustion were measured for the fuels methane and propane as a function of fuel-air equivalence ratio ϕ, initial pressure T_i, and wall temperature T_B and residual gas mass fraction f_I. The results are shown for stoichiometric mixtures in Fig 1 where the hydrocarbon concentrations $[N_C]$ are plotted as a function of the unburned gas concentration $[N_u]$. It can be seen that $[N_C]$ increases linearly with $[N_u]$ at a rate which is independent of the initial gas temperature T_B. This strongly suggests that the major source of the hydrocarbon observed came from a crevice into which the flame could not propagate. Although considerable effort was devoted to eliminating crevice, inspection of the bomb after the measurements were completed, revealed an unsealed crevice behind a ceramic insulator on the high voltage ignition electrode. The volume of this crevice was consistent with the slope of the data in Fig. 1.

An estimate of the hydrocarbon concentration from non-crevice sources $[N_{Cnc}]$ was obtained from the intercepts of the lines in Fig. 1. The most probable source of non-crevice hydrocarbons is the wall quench layer. If this is true, then the mass of carbon per unit wall area for both methane and propane having equivalence ratios between 0.8 and 1.2 is found to be of order 0.02 ug/cm^2. This is less than 5% of the value expected for an unoxidized single wall quench layer. In a typical automotive engine, such an oxidized quench layer would produce exhaust hydrocarbon fractions less than 10 ppmC. By comparison a crevice volume of 10 mm^3, roughly that of the void volume of one turn of the thread on a spark plug, would produce 100 ppmC in the exhaust. We are thus lead to the important conclusion that under normal operating conditions quench layers will be a negligible source of exhaust hydrocarbons in automotive engines. By the same token the elimination of crevices in engines should lead to significant reductions in

hydrocarbon emissions.

Reports:

1) Metghalchi, M., and Keck, J.C., "Laminar Burning Velocity of Propane-Air Mixtures at High Temperature and Pressure," Paper No. CSS/CI-79-04 presented at the Central States Meeting of the Combustion Institute, Columbus, Indiana, April 1979.

2) Metghalchi, M., and Keck, J.C., "Laminar Burning Velocity of Propane-Air Mixtures at High Temperature and Pressure," Combustion and Flame 38 143 (1980).

3) Sellnau, M.C., Springer, G.S. and Keck, J.C., "Measurements of Hydrocarbon Concentrations in the Exhaust Products from a Spherical Combustion Bomb," Paper No. 810148 presented at the SAE International Congress and Exposition Detroit, Michigan, February, 1981.

4) Keck, J.C., "Thermal Boundary Layer in a Gas Subject to a Time Dependent Pressure," Letters in Heat and Mass Transfer, 8 313, (1981).

5) Metghalchi, M. and Keck, J.C., "Burning Velocities of Mixtures of Air with Methanol, Isooctane and Indolene at High Pressure and Temperature," submitted to Combustion and Flame, August, 1981.

Theses:

1) Metghalchi, M., "Laminar Burning Velocity of Mixtures of Air with Indolene Isooctane, Methanol and Propane," Ph.D. Thesis, Dept. of Mech. Eng., M.I.T., February, 1980.

2) Sellnau, M.C., "Laminar Head-On Flame Quenching an a Spherical Combustion Bomb," M.S. Thesis, Dept. of Mech. Eng., M.I.T., February 1981.

Participating Personnel:

Professors James C. Keck (Principal Investigator), G.S. Springer (Visiting), W.C. Unkel.

Research Assistants: Mohamad Metghalchi (Received Ph.D. February 1980)
Mark C. Sellnau, (Received M.S. February 1981)

TABLE 1

A. Parameters B_m and B_2 obtained by fitting the expression

$$S_{uo} = B_m + B_2 (\phi - \phi_m)^2$$

to the data in Table 2 using the values of ϕ_m given in Table 3B. Δ is the standard deviation of a point from the fitted curve.

	ϕ_m	B_m cm/sec	B_2 cm/sec	Δ cm/sec
Methanol	1.11	36.92	-140.51	1.99
Propane	1.08	34.22	-138.65	1.23
Isooctane	1.13	26.32	- 84.72	0.19
RMFD-303*	1.13	27.58	- 78.34	0.81

*Vapor above liquid at 298 K

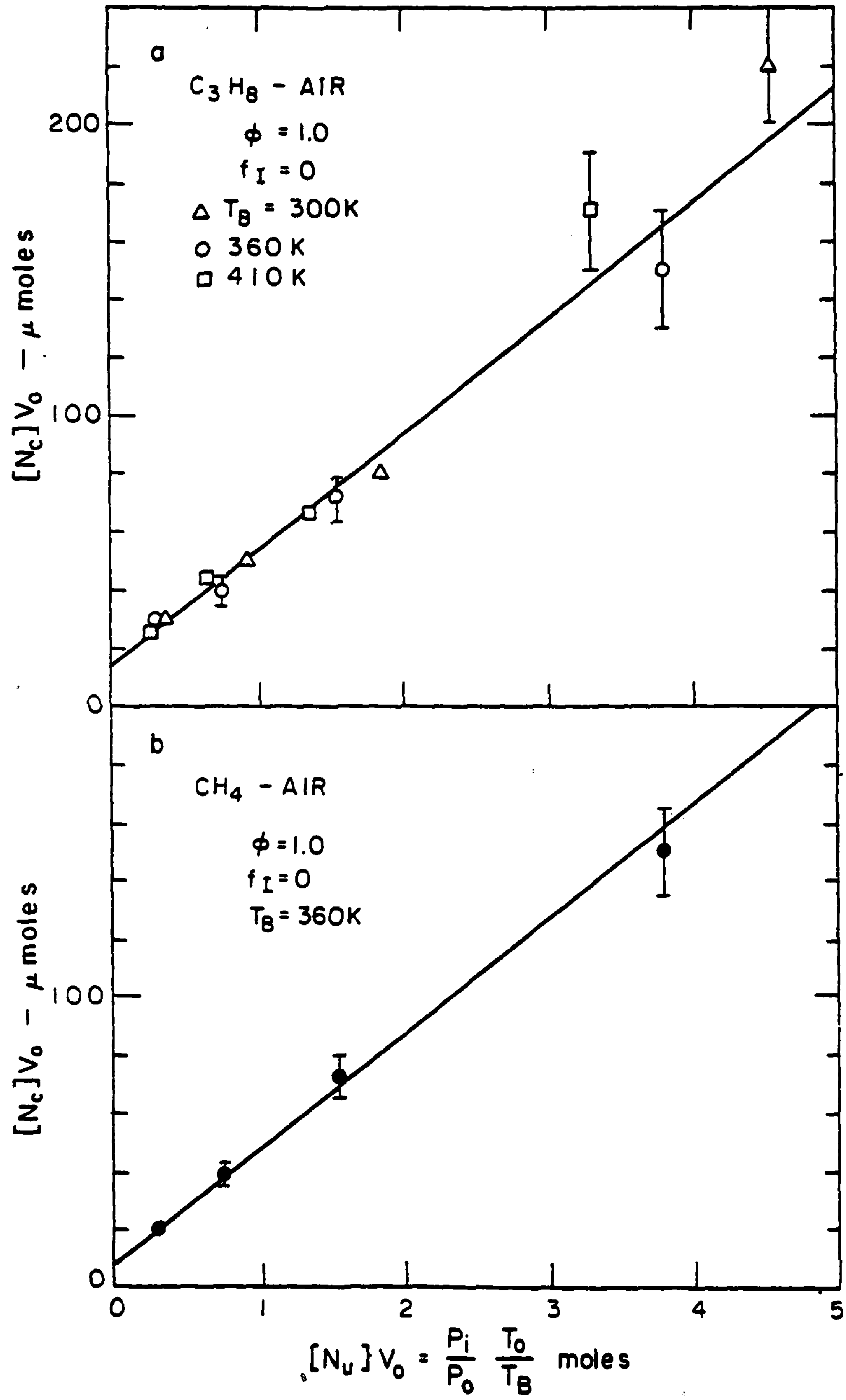
a
C_3H_8 - AIR
ϕ = 1.0
f_I = 0
T_B = 300K
360 K
410 K
b
CH_4 - AIR
ϕ = 1.0
f_I = 0
T_B = 360K
$[N_c]V_o$ — μ moles
$[N_u]V_o = \frac{P_i}{P_o}\frac{T_o}{T_B}$ moles
0
100
200
0
1
2
3
4
5

Fig. 1

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